Progress in understanding the nuclear effects in DIS

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Outline

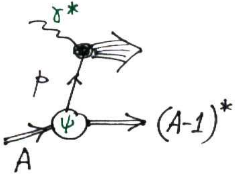
- Outline of a model of nuclear DIS.
- Study of consistency between different measurements of nuclear effects in DIS.
- DY data (E772 experiment) and nuclear antiquarks.
- Data/Theory comparison for neutrino differential cross sections.

Nuclear DIS in Impulse Approximation

In impulse approximation (IA) the major corrections are due to nucleon momentum distribution and its energy spectrum. Assuming bound nucleon momentum and energy nonrelativistic we have:

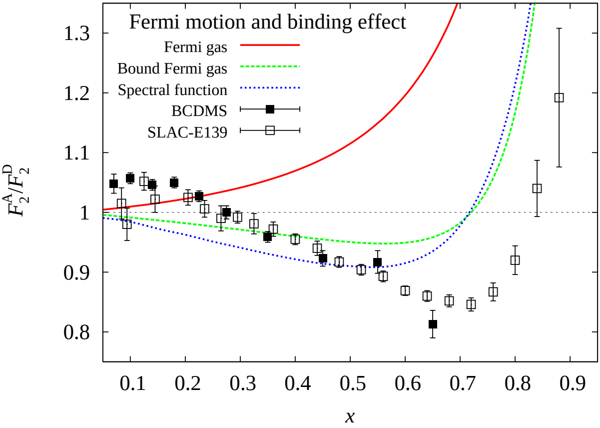
$$F_2^A(x,Q^2) = \int \mathrm{d}^4p\,\mathcal{P}_A(p)\left(1+\frac{p_z}{M}\right)F_2^N(x',Q^2,p^2),$$

$$x = \frac{Q^2}{2Mq_0}, \quad x' = \frac{Q^2}{2p\cdot q} \approx \frac{M\,x}{p_0+p_z}$$



Bound nucleon momentum and binding energy effect is driven by nuclear spectral function, which describes probability to find a bound nucleon with momentum $\boldsymbol{p}$ and energy $p_0 = M + \varepsilon$:

$$\mathcal{P}_A(p) = \sum_{(A-1)_n} \left|\langle (A-1)_n, -\boldsymbol{p}|\psi(0)|A\rangle\right|^2 \delta(\varepsilon + E_n(A-1) - E_0(A)).$$



It is important to treat Fermi motion and nuclear binding effects properly in IA. However, consideration of only these effects is not enough for quantitative undestanding of data. IA should be corrected for a number of other nuclear effects.

Model vs. Data

Motivation:

- Develop a model which would account for a major nuclear effects:
  - Realistic nuclear spectral function with a mean-field and correlation contributions.
  - Nuclear meson field contribution (needed for consistency).
  - Off-shell correction to bound nucleon structure function (recall additional dependence on p^2 for virtual nucleon).
  - Nuclear (anti)shadowing corrections due to multiple coherent interaction of hadronic component of intermediate boson.
  - Proper treatment of isoscalar and isovector contributions

$$F_i^A = F_i^{p/A} + F_i^{n/A} + \delta_\pi F_i + \delta_{\mathrm{coh}} F_i, \quad i = T, L, 3$$

- Perform systematic studies of data and test the model.

This program has been carried out and the main results were reported in *S.K. & R.Petti, NPA765(2006)126; PRD76(2007)094023*.

Data can be understood if we consider off-shell correction (along with other corrections)

$$F_2^N(x, Q^2, p^2) \approx F_2^N(x, Q^2) \left(1 + \delta f(x) \frac{p^2 - M^2}{M^2}\right)$$

The function δf assumed to be Q^2 independent and its x dependence was treated phenomenologically:

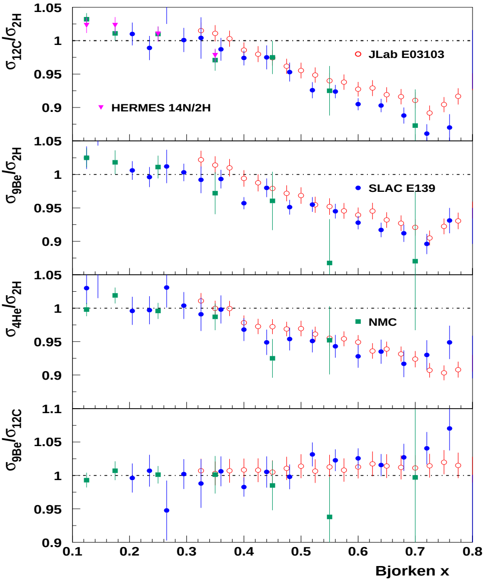
$$\delta f(x) = C_N (x - x_0)(x - x_1)(1 + x_0 - x)$$

The parameters C_N, x_0, x_1 are common for all nuclei, as by definition $\delta f(x)$ describes off-shell continuation of a free nucleon structure function.
The model leads to a very good agreement with data on nuclear EMC effect. The x, Q^2 and A dependencies of the EMC ratios are reproduced for all studied nuclei ($^4\mathrm{He}$ to $^{208}\mathrm{Pb}$) in a 4-parameter fit. For detailed discussion and comparison with data see *S.K. & R.P., Nucl. Phys. A765(2006)126*. Quality of description is illustrated in the following Table.

Targets	χ^2/DOF						
	NMC	EMC	E139	E140	BCDMS	E665	HERMES
^{4}He/^{2}H	10.8/17		6.2/21				
^{7}Li/^{2}H	28.6/17						
^{9}Be/^{2}H			12.3/21				
^{12}C/^{2}H	14.6/17		13.0/17				
^{9}Be/^{12}C	5.3/15						
^{12}C/^{7}Li	41.0/24						
^{14}N/^{2}H							9.8/12
^{27}Al/^{2}H			14.8/21				
^{27}Al/^{12}C	5.7/15						
^{40}Ca/^{2}H	27.2/16		14.3/17				
^{40}Ca/^{7}Li	35.6/24						
^{40}Ca/^{12}C	31.8/24					1.0/5	
^{56}Fe/^{2}H			18.4/23	4.5/8	14.8/10		
^{56}Fe/^{12}C	10.3/15						
^{63}Cu/^{2}H		7.8/10					
^{84}Kr/^{2}H							4.9/12
^{108}Ag/^{2}H			14.9/17				
^{119}Sn/^{12}C	94.9/161						
^{197}Au/^{2}H			18.2/21	2.4/1			
^{207}Pb/^{2}H						5.0/5	
^{207}Pb/^{12}C	6.1/15					0.2/5	

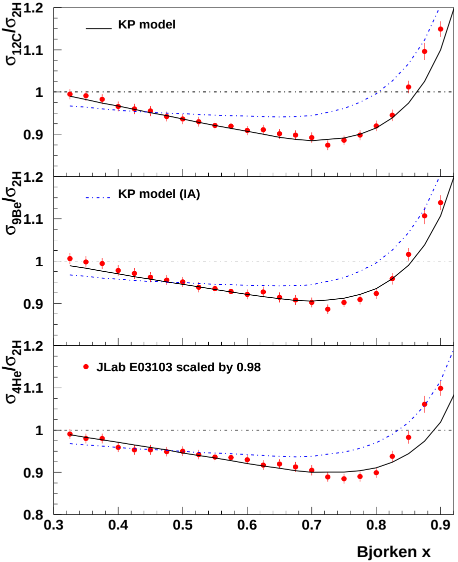
Values of χ^2/DOF between different data sets with $Q^2 \geq 1$ GeV^2 and the predictions of KP model *NPA765(2006)126; PRC82(2010)054614*. The sum over all data results in $\chi^2/\mathrm{DOF} = 466.6/586$.

Consistency of different experiments



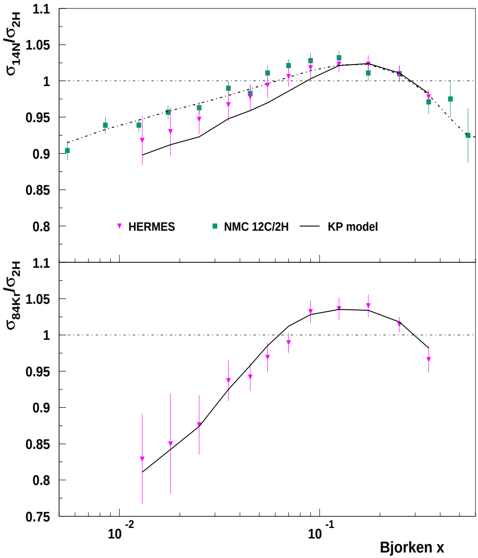
- Shapes of all nuclear cross-section ratios are consistent
- Evaluate χ^2 for each pair of experiments in coarse x-bins within the overlap region of the data sets
- Consistent overall normalization for SLAC E139, NMC and HERMES data sets
- The new JLab E03-103 data is systematically above previous measurements resulting in a $\chi^2/d.o.f. = 42.7/12$ with respect to SLAC E139 data on the same targets
- An overall normalization factor 0.98 for all JLab E03-103 points improves the statistical consistency with SLAC E139 data to $\chi^2/d.o.f. = 8.8/12$

Predictions for E03-103



- Apply overall normalization factor 0.98 to JLab data on $^4\mathrm{He/D}$, $^9\mathrm{Be/D}$ and $^{12}\mathrm{C/D}$
- Very good agreement of our predictions with JLab E03-103 for all nuclear targets: $\chi^2/d.o.f. = 26.3/60$ for $W^2 > 2$ GeV^2 (for more details see SK and RP, arXiv:1004.3062 [hep-ph])
- Note that this is not a fit. Nuclear corrections at large x is driven by nuclear spectral function, the off-shell function $\delta f(x)$ was fixed from previous studies.
- A comparison with the Impulse Approximation demonstrates that the off-shell correction is crucial to describe the data leading to both modification of the slope and position of the minimum of the EMC ratios.

Predictions for HERMES



- A good agreement of our predictions with HERMES data for $^{14}\mathrm{N}/\mathrm{D}$ and $^{84}\mathrm{Kr}/\mathrm{D}$ with $\chi^2/d.o.f. = 14.7/24$
- A comparison with NMC data for $^{12}\mathrm{C}/\mathrm{D}$ shows a significant Q^2 dependence at small x in the shadowing region related to the cross-section for scattering of hadronic states off the bound nucleons nucleons.

  The model correctly describes the observed x and Q^2 dependence.

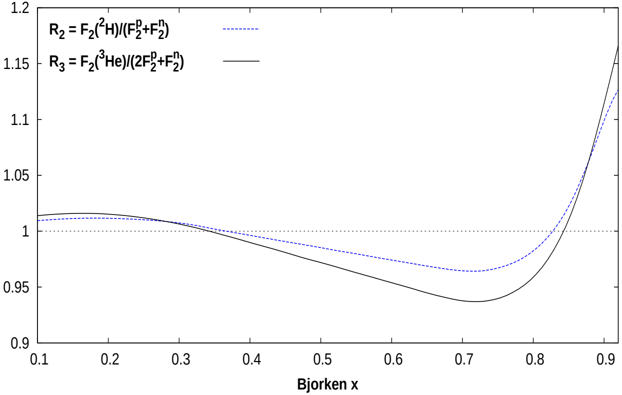
The $^3\mathrm{He}/\mathrm{D}$ and D/p data and F_2^n/F_2^p

- The $^3\mathrm{He}/\mathrm{D}$ data allows extraction of F_2^n/F_2^p. Comparison of F_2^n/F_2^p extracted from D/p and $^3\mathrm{He}/\mathrm{D}$ data provides a consistency test.
- D/p ratio. If we know $R_2 = F_2^D/(F_2^p + F_2^n)$ then we can extract F_2^n/F_2^p:

$$F_2^n/F_2^p = 2\mathcal{R}(\mathrm{D/p})/R_2 - 1$$

- $^3\mathrm{He}/\mathrm{D}$ ratio. In order to extract F_2^n/F_2^p we need to know both R_2 and $R_3 = F_2^{3\mathrm{He}}/(2F_2^p + F_2^n)$:

$$F_2^n/F_2^p = (2-z)/(z-1), \text{ with } z = \tfrac{3}{2}\mathcal{R}(^3\mathrm{He}/\mathrm{D})R_2/R_3$$



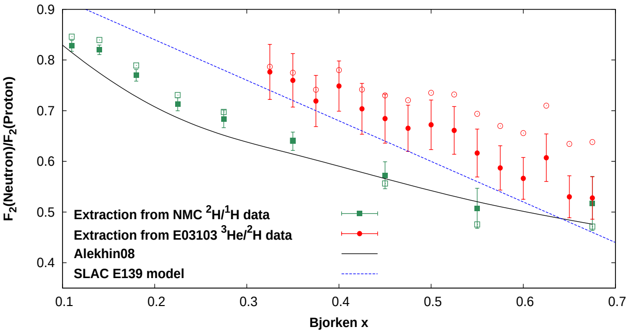
R_2 and R_3 were calculated at the values of x and Q^2 of E03-103 kinematics for $x > 0.3$ and at fixed $Q^2 = 3$ GeV^2 for $x < 0.3$.

The Paris wave function was used for the deuteron, while the Hannover spectral function was used for $^3\mathrm{He}$.

- R_2 and R_3 are similar. A dip at $x \sim 0.7$ is somewhat bigger for R_3 because of stronger binding in ^{3}He.

- Nuclear effects cancel at $x \approx 0.35$, which is consistent with the measurement of EMC effect in other nuclei.

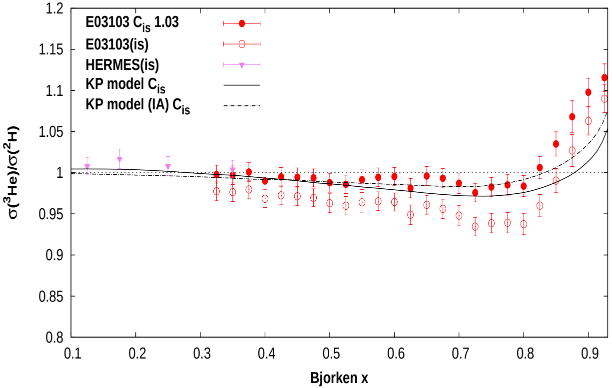
Extraction of F_2^n/F_2^p



Extraction of F_2^n/F_2^p with the full treatment of nuclear effect (full symbols) and also with no nuclear effects ($R_2 = R_3 = 1$, open symbols).

- Significant mismatch in F_2^n/F_2^p extracted from different experiments. At $x \sim 0.35$, where nuclear corrections are negligible, the F_2^n/F_2^p from E03-103 is 15% higher than that from NMC.
- Normalization of F_2^n/F_2^p is directly related to normalization of $^3\mathrm{He/D}$. Requiring F_2^n/F_2^p from E03-103 match NMC, we obtain a renormalization factor of $1.03^{+0.006}_{-0.008}$ for $^3\mathrm{He/D}$ data.

^{3}He/D from HERMES and E03-103 experiments



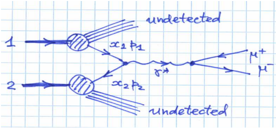
To correct for proton excess, HERMES applies the factor

$$C_{is} = \frac{AF_2^N}{ZF_2^p + NF_2^n}$$

with F_2^n/F_2^p from NMC. The E03-103 experiment does it differently, however correction factors are known.

- An unbiased way would be to compare uncorrected data, or corrected in a similar way. However, HERMES exact correction factors are lost. We uncorrect E03-103 data and then apply C_{is} together with the factor 1.03.
- After renormalization, E03-103 and HERMES data agree at the overlap ($x = 0.35$). Our calculation agree with both data (except the region $x > 0.8$).

Drell–Yan nuclear data



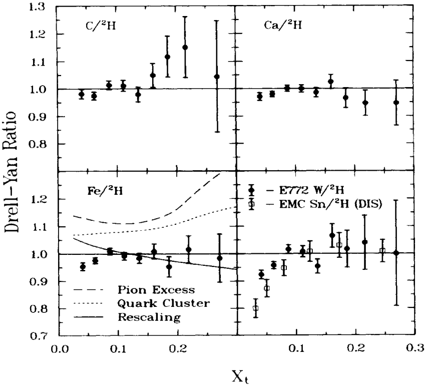


FIG. 3. Ratios of the Drell-Yan dimuon yield per nucleon, $Y_A/Y_{^2\mathrm{H}}$, for positive x_F. The curves shown for Fe/^{2}H are predictions of various models of the EMC effect. Also shown are the DIS data for Sn/^{2}H from the EMC (Ref. 4).

Drell-Yan production of a lepton pair in hadron collisions:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_B \mathrm{d}x_T} = \frac{4\pi\alpha^2}{9Q^2} K \sum_a e_a^2 \left[q_a^B(x_B)\bar{q}_a^T(x_T) + \bar{q}_a^B(x_B) q_a^T(x_T) \right]$$

$$x_T x_B = Q^2/s,$$
$$x_B - x_T = 2q_L/\sqrt{s} = x_F$$

Selecting small Q^2/s and large x_F we probe the target's sea. In E772 experiment $s = 1600\ \mathrm{GeV}^2$. At $x_F = x_B - x_T > 0.2$ the process is dominated by $q^B \bar{q}^T$ annihillation. The ratio of DY yields:

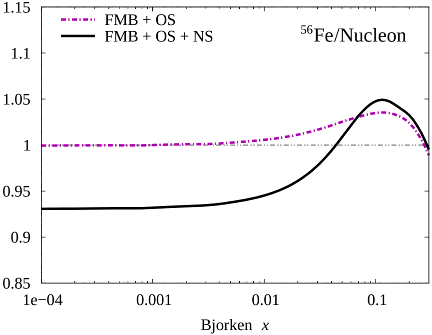
$$\frac{\sigma_A^{\mathrm{DY}}}{\sigma_B^{\mathrm{DY}}} \approx \frac{\bar{q}_A(x_T)}{\bar{q}_B(x_T)}$$

Nuclear sea and valence quark distributions

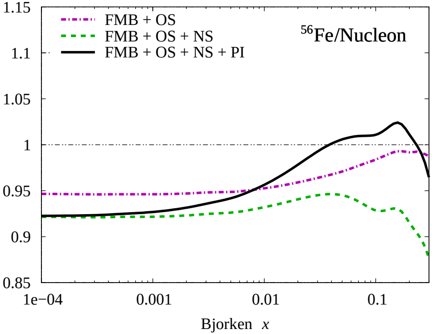
Nuclear corrections for antiquark distribution $\delta\mathcal{R}_{\rm sea} = \delta\bar q_A/\bar q_N$ follow directly from nuclear corrections for C-even $q+\bar q$ and C-odd $q-\bar q = q_{\rm val}$ combinations $\delta\mathcal{R}^{(+)}$ and $\delta\mathcal{R}^{(-)}$:

$$\delta\mathcal{R}_{\rm sea} = \delta\mathcal{R}^{(+)} + \frac{q_{\rm val/N}(x)}{2\bar q_N(x)}\left(\delta\mathcal{R}^{(+)} - \delta\mathcal{R}^{(-)}\right)$$

$\delta\mathcal{R}_{\rm val} = \delta\mathcal{R}^{(-)}$ at $Q^2 = 20$ GeV^2

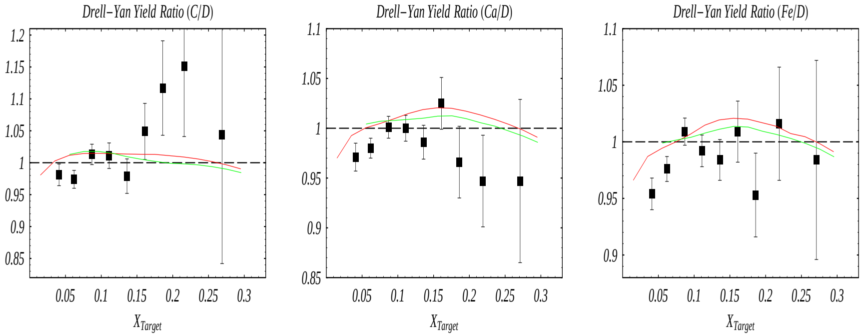


$\delta\mathcal{R}_{\rm sea}$ at $Q^2 = 20$ GeV^2



Note a remarkable *cancellation* between pion and shadowing effects for nuclear antiquark distribution for large $x \sim 0.1 - 0.3$.

Comparison with Drell-Yan data



Calculations are in reasonable agreement with data on DY ratios. Note that the mass of dimuon pair was not exactly known from E772 data and calculation was done for a fixed $Q^2 = 20$ GeV^2.

The cancellation from shadowing allows to reconcile nuclear pion excess with DY data.

Neutrino cross sections

(Anti)neutrino differential cross sections in terms of Bjorken x and inelasticity y:

$$\frac{\mathrm{d}^2\sigma_{\mathrm{CC}}^{(\nu,\bar\nu)}}{\mathrm{d}x\mathrm{d}y} = \frac{G_F^2 ME}{\pi(1+Q^2/M_W^2)^2}\left[Y_+ F_2^{\nu,\bar\nu} - y^2 x F_L^{\nu,\bar\nu} \pm Y_- x F_3^{\nu,\bar\nu}\right],$$

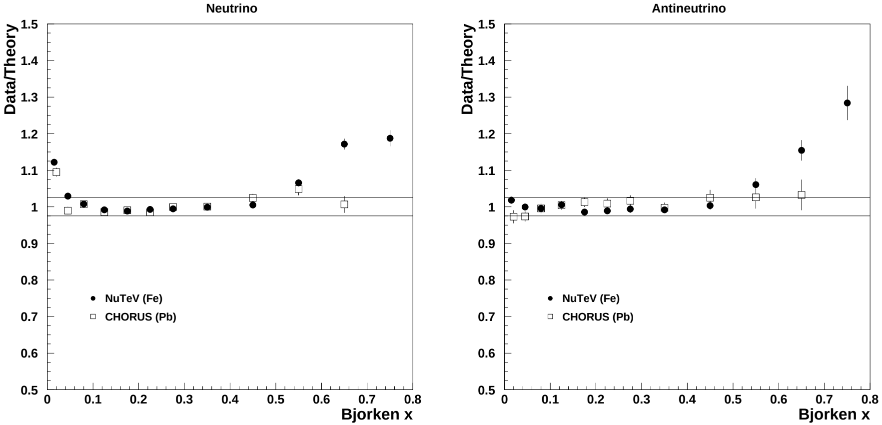
$$Y_+ = \frac{1}{2}\left[1+(1-y)^2\right] + \frac{M^2x^2y^2}{Q^2}, \quad Y_- = \frac{1}{2}\left[1-(1-y)^2\right].$$

Recently published cross-section data:

NuTeV data on $^{56}\mathrm{Fe}$:
about $1400\nu + 1200\bar\nu$ data points for $35 < E < 340$ GeV, $0.015 < x < 0.75$, $0.05 < y < 0.95$.

CHORUS data on $^{208}\mathrm{Pb}$:
about $600\nu + 600\bar\nu$ data points for $25 < E < 170$ GeV, $0.02 < x < 0.65$, $0.1 < y < 0.8$.

Data/Theory pulls for cross sections



Data/model predictions by *S.K. and R.Petti, NPA 765 (2006) 126; PRD 76 (2007) 094023*. The x-point is the weighted average over available E and y. The solid horizontal lines indicate a $\pm 2.5\%$ band.

χ^2 analysis (not a FIT)

Cut	No. of data points Neutrino	No. of data points Antineutrino	χ^2/d.o.f. Neutrino	χ^2/d.o.f. Antineutrino
NuTeV (Fe)				
No cut	1423	1195	1.36	1.10
$x > 0.015$	1324	1100	1.15	1.08
$x < 0.55$	738	671	1.16	1.02
$0.015 < x < 0.55$	686	620	0.97	1.01
CHORUS (Pb)				
No cut	607	607	0.68	0.84
$x > 0.02$	550	546	0.55	0.83
$x < 0.55$	506	507	0.74	0.83
$0.02 < x < 0.55$	449	447	0.60	0.83

- Good agreement with CHORUS differential cross section data for $^{208}\mathrm{Pb}$ in the whole kinematical range.
- Good agreement with NuTeV cross sections for $^{56}\mathrm{Fe}$ for $0.015 < x < 0.55$.
- Excess of data/theory for NuTeV cross sections at large $x > 0.5$ for both ν and $\bar{\nu}$. This is not supported by CHORUS(Pb) (and also NOMAD(Fe) data – *Roberto Petti, private communication*).
- Excess of data over theory for both, NuTeV and CHORUS data at small x $(0.015 - 0.025)$ (also supported by preliminary NOMAD(Fe) data – *Roberto Petti, private communication*).

Summary

- A detailed model of nuclear DIS was developed and tested in applications to charged-lepton and neutrino DIS.
- Data-to-data analysis was performed that allows to spot possible issues in normalization of recent JLab measurements of nuclear ratios.
- An interesting cancellation was found between shadowing and nuclear pion correction in antiquark distributions. This observation was discussed in context of the E772 DY experiment.
- A detailed Data/Theory comparison was performed for neutrino differential cross sections from the NuTeV and CHORUS experiments.